IPW AF

Docket No.: 2328-050

JC112 DEC 21 2004 PATENT & TRADEMARK OFFICE

BEST AVAILABLE COPY

PATENT

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE BOARD OF PATENT APPEALS AND INTERFERENCES

In re Application of :

Appellant: Jian J. CHEN et al.

U.S. Patent Application No. 09/821,027 : Group Art Unit: 1763

Filed: March 30, 2001 : Examiner: CROWELL, ANNA M.

For: INDUCTIVE PLASMA PROCESSOR HAVING COIL WITH PLURAL WINDINGS AND METHOD OF CONTROLLING PLASMA DENSITY

Mail Stop Appeal Brief
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Attn: BOARD OF PATENT APPEALS AND INTERFERENCES

APPELLANTS' REPLY BRIEF (37 C.F.R. 1.192)

Commissioner for Patents
PO Box 1450
Alexandria, VA 22313-1450

December 21, 2004

Sir:

Appellants submit this Reply Brief as a result of the new issues, as well as the false facts and innuendos included in the Examiner's Answer. The false statements in the Answer lead appellants to the conclusion that the examiner is not suitable to handle this application. The false statements show a lack of objectivity by the examiner and/or ignorance by the examiner of the technology involved in the application.

INDEX

Table of Authorities

I. The Undetermined Status of Li et al., U.S. Patent 6,238,512.

The Li et al. reference is mentioned in the Answer (1) on page 17 in a general manner, (2) on page 19 in connection with the rejection of claims 12 and 34, (3) in the sentence bridging pages 20 and 21 in an attempt to counter appellants' argument that the examiner has apparently relied upon appellants' disclosure to arrive at the conclusion that a controller which causes a constant current to flow in a winding to be while causing current in the remainder of the coil to vary provides control for distribution and uniformity of the plasma, (4) on page 22 in an attempt to counter appellants' arguments with respect to claims 32 and 33, and (5) on page 26 in an attempt to counter appellants' argument concerning claims 12 and 32-34. The examiner also apparently incorrectly cites Li et al. in an attempt to counter the statement on page 16 of the brief that none of the references has a disclosure of varying power to achieve the claimed different distributions of electromagnetic fields. At each of these occurrences, except that on page 17, the Examiner falsely states Li et al. teaches that by controlling power applied to a plasma, plasma distribution is achieved (column 12, lines 19-37). Section II of this Brief discusses why this allegation concerning Li et al. is false.

The claims have never been rejected on Li et al. As page 17 of the Answer states, Li et al. is first made of record in the March 31, 2004 Advisory Action. The Advisory Action includes the single statement "Furthermore, Li et al. teaches that by controlling the power, plasma distribution is achieved (col. 12, lines 19-37)." However, appellants could not ascertain from the terse statement in the advisory action what the examiner was driving at when she cited Li et al. In contrast to the terse statement in the Advisory Action, the Answer cites Li et al. four times in connection with four different rejections. Appellants are still unable to determine, from the Answer, whether the examiner is relying on Li et al. as a reference to reject the claims. The examiner appears to be of the opinion that Li et al. has an impact on many of the claims, as discussed, *supra*. However, framing of the

issues by the examiner in Item (6) on pages 3 and 4 of the Answer would seem to imply that the examiner does not rely on Li et al. as a basis for rejection.

Appellants will refrain from requesting a remand to the examiner with regard to the Li et al. reference. This is because the Li et al. reference does not disclose what the examiner says it discloses. In addition, Li et al. is concerned with magnetron plasma devices that have no coils. In contrast, the claims under appeal are directed to processors having coils. Based on the foregoing, appellants believe (1) there is no need to clarify the record with regard to the examiner's reliance on Li et al. and (2) remand is not necessary.

II. The Examiner Falsely States Li et al. teaches that by controlling the power, plasma distribution is achieved (column 12, lines 19-37).

Column 12, lines 19-28 of Li et al. state:

> The density of the first plasma is dependent on the size of the high-frequency electric power output by the high-frequency oscillator 16. Accordingly, by controlling the size of this high-frequency power, the density of the first plasma can be controlled. Similarly, the density of the second plasma is dependent on the size of the high-frequency electric power output by the high-frequency oscillator 23. Accordingly, the density of the second plasma can be controlled by controlling the size of that high-frequency power (emphasis added).

This paragraph clearly indicates density of a first plasma depends on the size (i.e., value) of the high-frequency electric power output of oscillator 16 and density of the second plasma depends on the value of the electric output power of oscillator 23. The density of plasma is not the same as the distribution of the plasma. The density of a plasma is the number of charge particles per unit volume of the plasma. In contrast, the distribution of the plasma indicates where the charge particles are distributed, i.e., located, in the plasma.

Li et al. discloses a magnetron high-frequency plasma generating apparatus (col. 8, lines 15-17). The first plasma mentioned in col. 12, lines 19-28, is generated by the interaction of a first electric field produced by cylindrical electrode 15 on the sidewall of a chamber and a DC magnetic field produced by permanent magnets 27 and 28. The electric field produced by electrode 15 results from excitation of electrode 15 by source 16. The second plasma mentioned in col. 12, lines 19-28, is produced by interaction of a second electric field produced by upper electrode 21 and the DC magnetic field from permanent magnets 27 and 28. Electrode 21 is responsive to the output voltage of RF source 23. See col. 11, lines 28-61 of Li et al. Thus, the powers applied to the first and second electric fields respectively control the density of the first and second plasmas, as col. 12, lines 19-28 states.

Column 12, lines 29-37 of Li et al. states:

> Thus, by controlling the sizes of the <u>two</u> high-frequency electric powers, the plasma density distribution in the radial direction of the vacuum vessel 11 can be controlled. As a consequence, even when the gas pressure is low, a plasma can be generated that exhibits high density overall, and uniform density distribution, across the interior of the vacuum vessel 11, from the periphery thereof to the center thereof (emphasis added).

The foregoing portion of Li et al. means that plasma density distribution is controlled by varying the relative values of <u>two</u> electric fields that electrodes 15 and 21, which are at right angles to each other, produce. It does not mean, as falsely alleged repeatedly in the Answer, that controlling the power applied to an electrode that produces an electric field results in control of plasma distribution. The variable plasma distribution that Li et al. obtains occurs only as a result of the interaction of the two different plasmas.

If the Examiner relies on Li et al. to disclose what the Examiner alleges is knowledge generally available to one of ordinary skill in the art with regard to power controlling plasma distribution of a plasma produced by a coil, such reliance is completely erroneous. Li et al. has nothing to do with (1) controlling plasma distribution in coil based plasma processors and (2) discloses that power applied to an electrode controls plasma density, not plasma distribution. In addition, a disclosure in a single patent does not provide an indication of knowledge generally available to one of ordinary skill in the art.

III. Many of the Allegations in the Answer Concerning Tomioka et al. are False.

Page 23 of the Answer states "Tomioka et al. was merely applied for the teachings of a controller for directly varying the total output power." This is not true; the first sentence of the last paragraph at the bottom of page 6 of the final rejection states:

> Tomioka et al. teaches an inductive plasma processor comprising a controller 14 for directly varying the total output power the source supplies to the plural parallel connected windings.

Thus, the Final Rejection states that the examiner relied on Tomioka et al. to disclose directly varying the total power a source supplies to parallel connecting windings, not merely to directly vary total output power. By alleging that Tomioka et al. discloses directly varying the total output power applied to parallel connected windings, the examiner alleged, in the Final Rejection, that Tomioka et al. was closely related to Sato et al., which appellants admit discloses plural, parallel connected windings.

In their brief, appellants' have clearly shown that the reliance by the examiner on col. 8, lines 34-37, of Tomioka et al. to disclose the plural parallel connected windings is incorrect. Because the

examiner apparently realizes she must have some showing of Tomioka et al. disclosing a parallel coil concept, she now incorrectly relies on column 5, lines 40-55, of Tomioka et al. to "teach that the power is supplied to a parallel resonance circuit." However, column 5, lines 40-55, is not directed to a coil having plural parallel connected windings. This portion of Tomioka et al. indicates that a first parallel resonance circuit, including capacitors 5 and 6 and coil 3, is driven by a first RF source 7 and a second parallel resonance circuit, including capacitors 8 and 9 and coil 4, is driven by a second RF source 10. Thus, any reliance by the examiner on Tomioka et al. to disclose two parallel connected coil windings driven by a source having a directly controlled output power is wrong.

The statements in the last several sentences of the paragraph at the top of page 23 of the Answer are nonsense. These statements are that appellants' inner winding 40 and outer winding 42 are not physically in parallel, they are concentric and that there is no physical connection between the two windings, but simply current is supplied to each winding from one source. The claims do not refer to a physical relationship between appellants' windings. Instead, the claims define "plural parallel connected windings" and further require a current from the source to flow in parallel to the plural parallel connected windings; see claims 11, 30 and 31-34.

Section X, page 23, of the Answer, says the motivation to modify the output power source of Sato et al. with Tomioka et al. is to allow the frequency, phase and output power of the source to be controlled and thus enhance overall process control. While Tomioka et al. indicates the frequencies, phases and powers of power supplies 7 and 10 are <u>controlled</u> by controller 14, Tomioka et al. provides (1) no rationale as to why the powers of supplies 7 and 10 are controlled and (2) no disclosure that the powers of the sources are <u>varied</u>. Tomioka et al. indicates why the frequency of source 10 is shifted, from 13.56 MHz to 13.21 MHz. However, Tomioka et al. never says the

powers derived sources 7 or 10 are varied; the patent indicates the powers derived from these sources remain constant at 300 watts. The examiner ignores the possibility of Tomioka et al. controlling power to turn the power on and off. Hence, Tomioka et al. provides no basis for the examiner's conclusion that one of ordinary skill in the art would modify the Tomioka et al. output power to enhance process control, as alleged in Section X, page 23 of the Answer. The foregoing comments are also applicable to the statements by the examiner concerning the variable output power of Tomioka et al., as argued in Sections XI and XII of the Answer.

IV. The Examiner's Interpretation of 35 USC §103 is Wrong.

The examiner continuously states, throughout the Answer, that a rejection under 35 USC §103 is proper if the reference is capable of being modified. She admits repeatedly that she has ignored language in the claims because the claims define an intended result. She completely ignores appellants' citation of *In re Mills* and incorrectly relies on *In re Shreiber*, as well as *Hewlett-Packard v. Bausch & Lomb Inc.* Appellants will not repeat their discussion concerning *Hewlett-Packard* which appears on page 23 of their original Brief, and is not mentioned in the Answer. However, a discussion of many of appellants' claims, *vis a vis*, the *Mills* and *Schreiber* cases is now presented.

The claim considered by the court in *Mills* is:

> 6. Apparatus for producing an aerated cementitious composition, comprising
>
> a mixing chamber being open to atmosphere and containing mixing means,
>
> feed means for feeding ingredients comprising cement, foaming agent and liquid to the mixing chamber,
>
> `mixing means for mixing ingredients fed to the mixing chamber, pump means for pumping the mixed ingredients to a desired site and having a pump inlet connected to an outlet of the mixing chamber,

> drive motor means connected through gearbox means providing a pumping capacity of the pump means greater than the feed rate of the ingredients to the mixing chamber provided by the feed means, such that in operation air is drawn into the mixing chamber, and entrained in the mixed ingredients.

The key aspect of this claim is the requirement for "drive motor means connected through gear box means providing a pumping capacity of the pump means greater than the feed rate of the ingredients to the mixing chamber provided by the feed means, such that in operation air is drawn into the mixing chamber, and entrained in the mixed ingredients." The Board in *Mills*, like the examiner in the present case, stated "In our opinion, the differences between claim 6 and the Mathis (i.e., prior art) machine...lies solely in the functional language of the claim." The Board further found that Mathis teaches the use of separate input and output motors to permit the various mixing means and pumps to operate at different rates. The Board was of the opinion that the Mathis machine was capable of being operated in such a fashion as to cause the output pump to draw air into the mixing chamber so that it is entrained in the mixture. The Board, like the examiner in the present case, said that since Mills was claiming an apparatus, not a method, that the claim was rendered obvious by the Mathis machine.

The Federal Circuit did not agree with the foregoing rationale of the Board. The court stated "While Mathis' apparatus may be capable of being modified to run the way Mills' apparatus is claimed, there must be a suggestion or motivation in the reference to do so." The court then cited *In re Gordon*, 733 F.2d 900, 902, 221 U.S.P.Q. 1125, 1127 (Fed. Cir. 1984) for the statement "The mere fact that the prior art could be so modified would not have made the modification obvious unless the prior art suggested the desirability of the modification." The court found no suggestion and overruled the Board by making the following statement "The Board found that the difference

between the claimed subject matter and the prior art resided solely in functional language and that appellant had to show that the prior art device lacked the functional characteristics of the claimed device." The Board cited *In re Ludke*, 441 F.2d 660, 169 U.S.P.Q. 563 (C.C.P.A. 1971 for this proposition. The court noted that the *Ludke* decision was a rejection based on lack of novelty, not an obviousness rejection and made the following comment "It is not pertinent whether the prior art device possesses the functional characteristics of the claimed invention if the reference does not describe or suggest its structure."

Thus, the court refuted the examiner's position in this case, that a reference can be used as a basis for obviousness in a rejection under 35 USC §103, if the reference is capable of certain operation.

The claim primarily considered by the court in the *Shreiber* case is:

> A dispensing top for passing only several kernels of a popped popcorn at a time from an open-ended container filled with popped popcorn, having a generally conical shape and an opening at each end, the opening at the reduced end allows several kernels of popped popcorn to pass through at the same time, and means at the enlarged end of the top to embrace the open end of the container, the taper of the top being uniform and such as to by itself jam up the popped popcorn before the end of the cone and permit the dispensing of only a few kernels at a shake of a package when the top is mounted on the container.

This claim states that the opening at the reduced end allows several kernels of popped popcorn to pass through it. The claim does not say the reduced end has a shape and dimensions that allow several kernels of the popped popcorn to pass through at the same time. Hence, the statement is purely functional and is not tied to structure. Further, the claim considered by the Federal Circuit said the taper of the top is uniform and such as to by itself jam up the popped popcorn before the end of the cone. The prior art relied on by the PTO apparently disclosed a uniform taper. The claim did

not say that the uniform taper and the dimensions were such as to by itself jam up the popped popcorn. In other words, there was no structural statement in the *Shreiber* claim to distinguish it over the reference. This is in contrast to the requirement of the Mills claim which stated that the drive motor provided a pumping capacity. In addition, the court in *Shreiber* relied on inherency.

Appellants' claims structurally relate the result which is achieved, in a manner that is even more specific than that set forth in the Mills' claim. Claim 11, rejected *inter alia* on 35 USC §103, says different amounts of total power and different relative currents are supplied to the plural parallel connected windings as a result of (1) a controller coupled to a source and (2) variable impedance arrangements. The claim indicates the source total output power is varied to vary the total power the source supplies to the plural parallel connected windings and the values of components of the variable impedance arrangements are varied. This language is very much in line with the Mills' claim language the court said could not be ignored. It is altogether different from the Shreiber language that does not relate the functional claim language to any particular structure.

Claim 12 is rejected solely on the basis of 35 USC §103, based on the examiner's allegation that the references are <u>capable</u> of operating as defined (contrary to the *Mills*' decision). Claim 12 specifically states that the controller is arranged for varying the source total power and the variable impedance arrangements so that for different distributions of electromagnetic fields generated by and supplied by the different windings to the plasma, the current flowing in one of the windings remains substantially constant and the current in the remainder of the coil changes. Similar limitations, as discussed in the original Brief, appear, *inter alia*, in claims 21, 22, 23 and 31-34.

V. The Combination of Chu et al. and Chen et al. is Untenable.

Chu et al., in column 1, line 50, column 2, line 8, discusses inductively coupled plasma sources of the prior art. These inductively coupled plasma sources are of a type disclosed in the enclosed copy of the *Journal of Applied Physics*, Vol. 80, No. 3, August 1, 1996, pp. 1337-1344. Such inductively coupled plasma sources are illustrated in Figures 1 and 4 of Kushner et al. as including a single winding having several turns, wherein the winding extends over a large area of a quartz window, above a wafer workpiece. Chen et al. and the present application are broadly concerned with coils of the same type, i.e., large area coils that extend over a substantial portion of a window, above a workpiece. However, Chu et al. points to alleged problems with such inductively coupled plasma sources and indicates that Chan describes, in U.S. Patent 5,653,811, "a pioneering technique that has been developed to improve or, perhaps, even replace these conventional sources." The Chu et al. and Chan patents both include multiple small coils.

It is fundamental that a reference must be considered in its totality, particularly for a rejection based on obviousness. Because Chu et al. is concerned with a plasma source that would replace the type of plasma sources disclosed by Chen et al. and by the present application, one of ordinary skill in the art would not apply the Chen et al. teachings to Chu et al., or vice versa. Doing so, would fly in the face of the very purpose of Chu et al. to replace the types of processors disclosed by Chen et al., Kushner et al. and the present application.

The statement on page 20 in Section V of the Answer apparently refers to appellants' claim 12. Claim 12 requires a controller for varying the total power and the variable impedance arrangements that are coupled with the plural parallel connected windings so that for different distributions of electromagnetic fields generated by and supplied by the different windings to the

plasma, the current flowing in one of the windings remains substantially constant and the current in the remainder of the coil changes. In other words, when the controller causes electromagnetic fields having plural distributions to be applied to the plasma at different times, the controller causes the current flowing in one of the windings to be always the same and the current in the remainder of the coil, i.e., the other windings of the coil, to change. The examiner says Chu et al. discloses this concept by controlling the variable impedance arrangements and says column 5, lines 53-55 of Chu et al. indicates the impedance of tuning capacitors 85 (*sic*,; apparently 58) and the output power from each antenna (not power source that drives each antenna) can be adjusted to maintain the uniformity of a generated plasma. There is no mention in this portion or any portion of Chu et al. to different distributions of electromagnetic fields or any disclosure that the current flowing in one of the Chu et al. windings remains constant for the different distributions and the current in the remainder of the coil "changes for the different distributions."

VI. The Examiner Incorrectly Says Appellants' Apparatus Claims Include Limitations of Intended Use that can be Ignored.

The examiner repeatedly throughout the Answer, at least eleven times on pages 16-23, makes the statement that the various limitations of appellants' apparatus claims are considered to be intended use and are not given patentable weight in apparatus claims. In other words, the examiner basically admits that she has ignored what she considers to be the intended use limitations of claims 11, 12, 16, 18, 19, 20, 24, 25, 28-30, 31-39; in this regard, see page 16, last sentence (re claim 11); sentence bridging pages 17 and 18, regarding claim 31; sentence bridging pages 18 and 19, regarding claim 31; sentence bridging pages 18 and 19, regarding claims 21 and 34; sentence bridging pages 21

and 22, regarding claims 32 and 33; page 24, regarding claims 11, 12, 31-35, 37 and 39; page 25, regarding claims 12 and 32-34; sentence bridging pages 28 and 29, regarding claim 20; page 30, first paragraph, last sentence, regarding claims 16, 19, 24, 25, 28-30; sentence bridging pages 30 and 31, regarding claims 16, 19, 24, 25, 29 and 30; sentence bridging pages 31 and 32, regarding claim 18; page 33, second sentence, for a general statement. The examiner appears to rely on *In re Shreiber* and *Hewlett Packard vs. Bausch & Lomb* for this position.

However, neither *In re Shreiber* nor *Hewlett Packard vs. Bausch & Lomb* stands for the proposition that statements of intended use in a claim can be ignored. In the *Shreiber* case, the court found the function to be inherent in the prior art. Appellants, in the original Brief, pointed out that the examiner has made no attempt to show inherency. She continues along that path. Clearly, the *Hewlett Packard* case does not stand for the proposition that functional limitations in a claim can be ignored. It has been repeatedly held that not one word in the claim can be ignored. Hence, the examiner's basis for rejecting claims 11, 12, 16, 18, 19, 20, 24, 25, 28-30, 31-35, 37, 38, 39, is contrary to established law.

Further, the requirements of claims 11, 12, 16, 18, 19, 20, 24, 25, 28-30, 31-35, 37, 38 and 39 do not merely call for an intended result. For example, claim 20 includes the specific recitation of the power of "the source and the values of reactances of the impedance arrangements being such that (a) the maximum amplitude of a standing wave current in one of the windings differs from the maximum amplitude of a standing wave current in the remainder of the coil and (b) adjacent windings have standing wave current maxima that are radially opposite from one another." This is not a mere statement of intended result, but is a statement that the power and the values of the

reactances cause a result to be achieved. Such language is clearly consistent with the language approved by the Federal Circuit in *In re Mills*.

Many of the other claims are directed to a controller that varies certain parameters that cause a particular phenomenon or phenomena to be achieved. For example, claim 31 defines "a controller coupled with the AC source for varying the total amount of power applied by the source to the individual plural windings of the plural parallel connected windings so that for different distributions of electromagnetic fields different amounts of current are applied to the individual windings and different amounts of total power are applied by the source to the windings." Similarly, claim 32 requires "a controller arranged for varying the currents applied by the source to the windings for causing the electromagnetic field generated by the exterior winding to exceed the electromagnetic field generated by the remainder of the coil." Claims 33 and 34 include limitations similar to those of claim 32; claim 33 requires the controller to vary the current supplied by the source to the windings for causing the electromagnetic field generated by an exterior winding to be less than the electromagnetic field generated by the remainder of the coil, while claim 34 indicates the controller varies the current supplied by the source to the windings for causing the current flowing in one of the windings to remain substantially constant and the current in the remainder of the coil to change. These are limitations analogous to the aeration limitations found acceptable by the court in *Mills*.

The assertion that independent claims 25 and 28, and the dependent claims with a similar limitation, i.e., claims 16, 18, 19, 24, 29 and 30, include statements of intended use that have no patentable weight, i.e., can be ignored, is also wrong. The examiner incorrectly states that a statement of intended use arises from the requirements of these claims for the source frequency and the lengths of the windings or the length of the winding to be such that there are no substantial

standing current variations along the lengths of each winding. Her position that these limitations are to be given has no patentable weight is nonsense. Again, the examiner appears to rely on the *Shreiber* and *Hewlett Packard vs. Bausch & Lomb* decisions. However as discussed *supra*, the court in neither case found that functional statements in a claim can be ignored. The examiner has made no attempt whatsoever to show that the prior art discloses the foregoing requirements of independent claims 25 and 28 and dependent claims 16, 18, 19, 24, 29 and 30. Further, the allegation that the foregoing statement is a statement of intended use is wrong. The examiner has made no attempt to explain what the alleged intended use is. The claim defines how the source frequency and the lengths of the windings are related to achieve a particular result. The position of the examiner seems to be that if a claim defines a result, that result can be ignored. Clearly that is not the law.

VII. The Examiner Incorrectly Relies on What She Says is Knowledge Generally Available to One of Ordinary Skill in the Art.

Another consistent theme of the Answer is that knowledge generally available to one of ordinary skill in the art can be relied on by the examiner. In this regard, the examiner relies on Li et al. to disclose varying the power applied to the plasma to control plasma distribution; see the rejection of claims 12 and 34 in Section IV, page 19 of the Answer; Section VI, pages 20 and 21; Section VII, page 22, regarding claims 32 and 33, and the sentence bridging pages 25 and 26. As discussed *supra* in Section II of this Brief, the Li et al. reference does not disclose controlling plasma distribution by varying the power applied to the plasma, as incorrectly alleged by the examiner. Further, there is no showing that the Li et al. reference is knowledge generally available to one of ordinary skill in the art. The citation of a single patent does not provide an indication of knowledge generally available to one of ordinary skill in the art.

VIII. Miscellaneous Matters

There are numerous miscellaneous misstatements in the examiner's Answer, as discussed in this section of appellants' Reply Brief. These misstatements, in some cases, indicate a lack of objectivity by the examiner, and in other cases, an ignorance of the technology associated with the invention.

A. The Examiner Wrongly Equates Power and Frequency

On page 27, last line, and page 30, first sentence of the Answer, the examiner equates frequency to power by saying "However, Chu et al. states the output power 66 (i.e., frequency) is controlled directly (page 27)" and "However, Tomioka et al. states the output power 7 or 10 (i.e., frequency) is controlled." It is a basic proposition of electrical engineering that the power generated by an AC source is equal to the output voltage of the source multiplied by the current supplied by the source to the load, times the cosine of the phase angle between the voltage and current. The frequency derived by a source is the number of cycles per second that the source generates. In this regard, note the definitions of power and frequency on the enclosed copies of pages 1420 and 726 of *The American Heritage Dictionary*. These are basic aspects of electrical engineering. The failure of the examiner to know these basic aspects of electrical engineering brings into question the examiner's ability to make judgments concerning the present application.

B. The Amendment Filed with the Original Brief is not Acknowledged

Appellants filed an amendment with the original Brief. Since no statement regarding that amendment appears in Section IV of the Answer and Section XIII of the Answer indicates Appendix A of the Brief includes a correct copy of the appealed claims, appellants presume the amendment accompanying the Brief was entered.

C. The Examiner has Dropped the Rejection of Claim 18 Based on Chu et al. and Chen et al.

Issue F presented in appellants' Brief needs to be modified to indicate that the rejection of claim 18 based on Chu et al. and Chen et al. has been dropped; see page 27, first full paragraph of the Answer.

D. The Examiner Admits that She Ignores *In re Mills*

The examiner admits that her position with regard to rejecting a claim based on obviousness because an apparatus is capable of being controlled to achieve a particular result is contrary to decisions of the Federal Circuit, for example, *In re Mills*. In this regard, see Item (8), page 4 of the Answer. Of course, the examiner cannot take a position that is contrary to the decisions of the Federal Circuit.

E. The Examiner Mischaracterizes Section VII of the Original Brief

The objectivity of the examiner in handling the present application is seriously in doubt, in view of her statement on page 4, Item (7), with regard to the statement in Section VII of appellants' original Brief. Section VII of appellants' original Brief states:

> Separate arguments are presented for patentability of each of the claims, except for claims 35, 37 and 39. Appellants concede that claims 35, 37 and 39 rise and fall with the claims upon which they depend.

Section (7) of the Answer, on page 4, states:

> The rejection of claims 11-25 and 28-40 stand or fall together because appellants' brief does not include a statement that this grouping of claims does not stand or fall together and reasons in support thereof.

Appellants, by stating that separate arguments are presented for the patentability of each of the claims, except for claims 35, 37 and 39, and then going to state that claims 35, 37 and 39 rise and fall with the claims upon which they depend, clearly indicate that none of the claims being considered rise and fall with any other claims, except claims 35, 37 and 39. Further, the argument presented in Section VIII of appellants' original Brief specifically discusses the language of each of the claims under consideration, except claims 35, 37 and 39. Hence, there is no basis for the foregoing statement by the examiner in Section (7) of the Answer. The statement in Section (7) of the Answer demonstrates the examiner's hostility and lack of objectivity in connection with the application.

F. The Examiner Mischaracterizes the Number of References of Record

Section (9) of the Answer incorrectly states that the prior art of record consists of six references. In fact, there are many more references of record, in particular; see, e.g., the PTO-1449, submitted by appellants with the Information Disclosure Statements of July 5, 2001 and December 3, 2003.

G. The Motivation of the Examiner in Combining the References

The Answer, on page 19, second sentence, page 22, second sentence and page 25, last full sentence, states that the examiner has a motivation for achieving the current flows required by claims 12 and 34, to produce the electromagnetic fields generated by the apparatus of claims 32 and 33 and the current flows and electromagnetic fields of claims 12 and 32-34. The test for obviousness is not the examiner's motivation, which in this case appears to be to reject appellants' claims. Instead, the test for obviousness is the motivation of one of ordinary skill in the art. The examiner says her motivation for arriving at the controllers defined by the foregoing claims is to control the distribution and uniformity of the plasma. However, there is nothing in the cited prior art to indicate that a controller which controls output power of a source and the current in plural windings, as defined by appellants' claims, will result in a uniform plasma.

The alleged motivation set forth on page 27, Section XV of the Answer, that uniform plasma density is achieved by modifying Chu et al. as disclosed by Chen et al. is nonsense. The Chu et al. and Chen et al. structures are so different from each other that they would not be combined. Further, Chu et al. indicates that they are concerned with a plasma generator of a type entirely different from that of Chen et al. Chen et al., on page 5, lines 23-28, page 8, lines 4-6, indicates their invention is concerned with a transformer coupled plasma (i.e., TCP). Chu et al., in column 1, line 50 to column 2, line 8, and column 2, lines 21-39, indicate their alleged advance is in connection with a pioneering technique that has been developed to improve or perhaps even replace transformer coupled plasma sources of the type Chen et al. discloses. The foregoing portions of Chu et al. and Chen et al. would lead one of ordinary skill in the art to the conclusion that these references would not be combined by one of ordinary skill in the art.

H. The Examiner Mischaracterizes Claims 32 and 33

The discussion in Section VIII on page 22 of the Answer concerning claims 32 and 33 materially mischaracterizes the claims. Claims 32 and 33 require one of the plural parallel connected windings to be an exterior winding located so electromagnetic fields generated by it are in proximity to a peripheral wall of a vacuum plasma processor chamber and electromagnetic fields generated by the remainder of the coil is remote from the chamber of peripheral wall. The examiner's consideration of claims 32 and 33 ignores the fact that the remainder of the coil of claims 32 and 33 is the portion of the coil that is not the exterior winding. In Chu et al., if the coil 46 in proximity to the left wall of the chamber, as illustrated in Figure 1, is considered as the one winding that is in proximity to the peripheral wall of the chamber, the remainder of the coil includes the coil 46 that is in proximity to the right wall of the chamber. Hence, it is improper to interpret only the center coil 46 of Chu et al. as the remainder of the coil of claims 32 and 33.

I. The Examiner's Allegations Concerning Applying Zero Frequency and Zero Power to a Plasma Inducing Coil are Nonsense.

Section XVI, page 27 and Section XX, page 30 of the Answer repeat the nonsense concerning "zero" frequency and zero power. The examiner has not responded to the argument on page 22 of the original Brief that, if the source frequency were zero and/or no power were applied to the coil, no plasma would be generated.

CONCLUSION

The Answer includes numerous misstatements that call into question the suitability of the examiner to handle this application. The incorrect statements are intentional and/or due to a lack of understanding of basic principles of electrical engineering and physics. For example, equating frequency and power is wrong, stating that Li et al. varies power to control distribution of a plasma is wrong. The examiner attributes the variable power aspects of Tomioka et al. and Chu et al. to changing plasma distribution. There is nothing in either reference to indicate such a relationship and Li et al. certainly does not provide it.

The examiner's understanding of the law is wrong. Claim limitations cannot be ignored. The examiner cannot give statements of intended result no patentable weight. The decisions she cites in support of such a position do not stand for this proposition. Further, appellants' claims do not merely include statements of intended use.

Reversal of the rejection and allowance of all claims are in order.

To the extent necessary, Appellants petition for an extension of time under 37 C.F.R. 1.136. Please charge any shortage in fees due in connection with the filing of this paper, including extension of time fees, or credit any overpayments to Deposit Account 07-1337.

Respectfully submitted,

Lowe Hauptman Gilman & Berner, LLP

Allan M. Lowe - Registration No. 19,641
Attorney for Appellants

1700 Diagonal Road, Suite 300
Alexandria, Virginia 22314
Phone: 703-684-1111
Facsimile: 703-581-5499
AML:alw

M:\2328 LAM RESEARCH CORPORATION\2328-050\11-04 Reply Brief.doc

A three-dimensional model for inductively coupled plasma etching reactors: Azimuthal symmetry, coil properties, and comparison to experiments

Mark J. Kushner,[a] Wenli Z. Collison,[b] and Michael J. Grapperhaus
University of Illinois, Department of Electrical and Computer Engineering, 1406 West Green Street, Urbana, Illinois 61801

John P. Holland and Michael S. Barnes
Lam Research, Inc., 4650 Cushing Parkway, Fremont, California 94538

(Received 4 March 1996; accepted for publication 2 May 1996)

Inductively coupled plasma (ICP) etching reactors are rapidly becoming the tool of choice for low gas pressure, high plasma density etching of semiconductor materials. Due to their symmetry of excitation, these devices tend to have quite uniform etch rates across the wafer. However, side to side and azimuthal variations in these rates have been observed, and have been attributed to various asymmetries in pumping, reactor structure and coil properties. In this article, a three-dimensional computer model for an ICP etching reactor is reported whose purposes is to investigate these asymmetries. The model system is an ICP reactor powered at 13.56 MHz having flat coils of nested annuli powering Ar/N_2 and Cl_2 plasmas over a 20-cm diam wafer. For demonstration purposes, asymmetries were built into the reactor geometry which include a wafer-load lock bay, wafer clamps, electrical feeds to the coil, and specifics of the coil design. Comparisons are made between computed and experimentally measured ion densities and poly-silicon etch rates in Cl_2 plasmas. We find that the electrical transmission line properties of the coil have a large influence on the uniformity of plasma generation and ion fluxes to the wafer. [S0021-8979(96)08915-3]

I. INTRODUCTION

Inductively coupled plasma (ICP) reactors are being developed as high plasma density (10^{10}–10^{12} cm^{-3}), low gas pressure (< 10's mTorr) sources for etching, and deposition of semiconductor materials.[1–5] ICP plasma etching tools for 20 cm wafers have been demonstrated which have a high degree of uniformity for etch rates and selectivity as a function of azimuth and radius. Azimuthal asymmetries and side-to-side variations in these quantities, however, are not uncommon occurrences during tool development.[6] These asymmetries have been correlated with azimuthal variations in input and pumping of gases, circuit issues related to transmission line matching to the coil, and particulars of the reactor configuration. Modeling of plasma etching reactors, and ICP etch tools in particular, have significantly advanced over the past few years, and many two-dimensional models have been developed.[7–10] These models have been useful in investigating issues related power deposition, transport, and plasma chemistry. However, due to their limited dimensionality these models may not be able to address issues related to reactor asymmetries.

In this article, we describe a three-dimensional, time dependent model for ICP and reactive ion etching (RIE) reactors whose intent is to provide an infrastructure to investigate asymmetries in plasma etching and deposition tools. We discuss here results from the model for ICP reactors which demonstrate the effects of internal structures in the reactor and asymmetries in the inductively coupled electric field on the uniformity of plasma generation and ion densities. Computed ion densities and ion fluxes to the wafer are also compared to Langmuir probe measurements and poly-silicon etch profiles in Cl_2 plasmas. We find that asymmetries in the coil can produce radial or axial electric field components commensurate in magnitude to what is normally assumed to be a symmetric azimuthal component. The transmission line characteristics of the coil can also produce azimuthal variations in the coil current. These conditions produce commensurate variations in the inductively coupled electric field, electron heating, and ion production rates which may persist through the plasma to the plane of the wafer. Coil generated asymmetries in these quantities are reflected in the etch uniformity across the wafer. Geometrical asymmetries, such as wafer clamps and load lock bays for wafer handlers, also cause perturbations in the ion flux. We will describe the model in Sec. II and discuss results from the model for plasma properties in reactors having asymmetries in Sec. III. Comparisons are also made to electric probe measurements of ion densities and etching uniformity. Our concluding remarks are in Sec. IV.

II. DESCRIPTION OF THE MODEL

The model is a three-dimensional extension of a previously described two-dimensional simulation called the Hybrid Plasma Equipment Model (HPEM).[7,11] As a point of departure, the HPEM will first be briefly described followed by modifications we made to that model for the three-dimensional version, called HPEM-3D. The HPEM consists of an electromagnetic module (EMM), an electron Monte

[a]Electronic mail: mjk@uiuc.edu
[b]Present address: Lam Research, Inc., 4650 Cushing Parkway, Freemont, CA 94538.

Carlo simulation (EMCS), and a fluid-chemical kinetics simulation (FKS). The inductively coupled electromagnetic fields are produced by the EMM. Those fields are used in the EMCS to generate the electron energy distribution as a function of position and phase in the radio frequency (rf) cycle. The electron distributions are then used to produce electron transport coefficients and electron impact source functions. These values are transferred to the FKS in which the densities for all charged and neutral species are obtained, and Poisson's equation is solved for the electrostatic fields. The momentum equations for ions and neutral species can also be solved as an option, thereby accounting for inertial effects and gas flow. The densities, conductivities, and electrostatic fields obtained from the FKS are then transferred to the EMM and EMCS. This iterative cycle is repeated until a converged solution is obtained. Another option to the HPEM replaces the EMCS with a Boltzmann–Electron energy equation module (BEM). This option was used for the HPEM-3D, and so will be described below.

The HPEM-3D is functionally equivalent to the HPEM with added dimensionality. The coordinate system may be cylindrical (r,Θ,z) or Cartesian (x,y,z), and in this article results for a cylindrical coordinate system are presented. The EMM of HPEM-3D solves for (r,Θ,z) components of the complex inductively coupled electric field, $\mathbf{E}$. Following the usual procedure,[7–12] a wave equation is formulated from Maxwell's equations by assuming that the charge density $\rho=0$ and that the plasma is collisional. The latter assumption results in currents in the plasma being described by $\mathbf{J}=\sigma\mathbf{E}$, where σ is the conductivity. The wave equation we implemented is

$$\nabla\cdot\frac{1}{\mu}\nabla\mathbf{E}=\frac{\partial^2(\epsilon\mathbf{E})}{\partial t^2}+\frac{\partial(\sigma\mathbf{E}+\mathbf{J}_0)}{\partial t}. \tag{1}$$

J_0 represents externally driven coil currents we obtain from a transmission line model for the coil (see below). Equation (1) is solved in the frequency domain by assuming the electric field is harmonic,

$$\mathbf{E}(\mathbf{r},t)=\mathbf{E}(\mathbf{r})\exp\{i[\omega t+\phi(\mathbf{r})]\}. \tag{2}$$

The conductivity we used is complex and is the sum of the conductivities of each plasma species,

$$\sigma=\sum_j\frac{q^2n_j}{m_j\nu_j\left(1+\dfrac{i\omega}{\nu_j}\right)}, \tag{3}$$

where n_j, m_j, and ν_j are the density, mass, and momentum transfer collision frequency of species j. This procedure results in three-dimensional partial differential equations for the electric field components E_r, E_Z, and E_θ which are iteratively solved in the frequency domain using the method of successive-over-relaxation (SOR).[7]

The externally driven currents in the coil are obtained by representing the coil as a transmission line beginning at the rf generator and terminating at ground.[12] The electrical length of the transmission is mapped to the spatial dimension along the path of the coil. The coil-plasma system is further represented as a single turn transformer.[13] Following conventional transformer theory, the impedance of the secondary (the plasma) can be represented by an equivalent transformed impedance on the primary side of the circuit (the coil). Each discrete element (labeled i) of the transmission line is composed of a sum of impedances

$$Z_i=-i\omega L_{ci}+i/\omega C_{pi}+R_c+Z_{Ti}, \tag{4}$$

where L_c is the physical inductance of the coil, C_p represents capacitive coupling of the coil to the plasma, R_c is Ohmic resistance of the coil, and Z_T is the transformed impedance of the plasma. Apportionment of these quantities along the coil to each element in the transmission line is performed on a geometrical basis. The coil voltage and current (amplitude and phase) of each element along the coil are obtained by solving the resulting circuit equation in the frequency domain. This treatment therefore addresses only the fundamental frequency of excitation. The amplitude of the driving voltage is derived by requiring that the power deposition in the plasma be a specified value. The transmission line currents are then used as driving terms in the solution of the wave equation. These currents are periodically updated during the iterative SOR solution of the wave equation for the electric fields.

The form of the transformed impedance we used has been discussed by Piejak *et al.*[13] The transformed impedance of the plasma is given by

$$Z_T=\left(\frac{\omega M}{Z_p}\right)^2\left[-i\omega L_p+R_p\left(1-i\frac{\omega}{v_m}\right)\right],\quad M^2=kL_cL_p, \tag{5a}$$

$$Z_p^2=\left(\omega L_p+\frac{\omega}{v_m}R_p\right)^2+R_p^2, \tag{5b}$$

where L_p is the discharge inductance of the plasma, ν_m is the momentum transfer collision frequency in the plasma, R_p is the plasma resistance, and k is the transformer coupling coefficient, estimated to be 0.25 here. We calculated an effective plasma resistance from

$$R_p=\frac{\displaystyle\int\mathbf{j}\cdot\mathbf{E}d^3r}{\displaystyle\frac{1}{2\pi}\int\left(\int\mathbf{j}(\theta)\cdot d\mathbf{A}\right)^2d\theta}, \tag{6}$$

where $j=\sigma E$ is the plasma current and the integral in the denominator is over the cross sectional area. The numerator is the total power deposition. The denominator is the circulating current. The effect of this integral is to more heavily weight plasma transport coefficients in regions of the plasma where the electric field is large.

In the cases discussed here, the EMCS typically used in the two-dimensional HPEM was replaced by the Boltzmann-electron energy equation module. This decision was made based on the large memory requirements for storing the electron energy distribution at each spatial location in the 3D mesh, and the large number of pseudoparticles required to obtain acceptable statistics. In the BEM, we solve an electron energy equation for average energy ϵ,

$$\frac{\partial(n_e\epsilon)}{\partial t}=P(\epsilon)-n_e\sum_i N_i\kappa_i-\nabla\left(\frac{5}{3}\epsilon\varphi-\lambda\nabla T_e\right), \tag{7}$$

where T_e is the electron temperature [defined as $(2/3)\epsilon$], n_e is the electron density (obtained from the FKS), P is the electron power deposition (obtained from the EMM and FKS), κ_i is the rate coefficient for power loss (eV-cm^{3}s^{-1}) for collisions of electrons with species i having density N_i (the latter obtained from the FKS, λ is the electron thermal conductivity, and φ is the electron flux (obtained from the FKS). This equation is solved in the steady state in three-dimensions using an implicit SOR technique. An electron temperature of 0.05 eV is assigned to all surfaces in contact with the plasma and the thermal conductivity is assigned appropriate values across the sheath commensurate with the electron density in the sheath. This effectively results in an adiabatic boundary condition.

The electron transport coefficients and rate coefficients for use in solving Eq. (7) are obtained by solving Boltzmann's equation (BE) using a two-term spherical harmonic expansion.[14] BE is parameterized over a range of E/N, and a table of transport coefficients as a function of ϵ is constructed. This table is then interpolated during solution of Eq. (7). The electron energy equation and BE (to generate the lookup table) are solved on each iteration through the simulation based on updated densities, mole fractions, fluxes, and power deposition.

Charged and neutral particle densities are generated, and Poisson's equation is solved, in the FKS. To minimize computing resources, the ion momentum equations were not solved in the cases presented here, and so drift-diffusion expressions were used for all species. Poisson's equation is solved using a semi-implicit technique as described in Ref. 7. In doing so, the time step is typically 10^3–10^4 times longer than the dielectric relaxation time. All fluxes and spatial derivatives are couched in finite difference form using a conservative donor cell technique. The transport equations are integrated in time to a quasisteady state solution using acceleration techniques to speed the convergence of the model. Although, the capability exists to rf bias any surface in the reactor, the results presented here will not consider substrate bias; only the coil is powered. Except for the added dimensionality, the algorithms used in the FKS are essentially the same as in the 2D HPEM.

III. ASYMMETRIES IN INDUCTIVELY COUPLED PLASMA REACTORS

The first cases discussed here will be for an idealized ICP reactor, schematically shown in Fig. 1, powered by a flat coil at 13.56 MHz set on top of a quartz window. The wafer is 20 cm in diameter. The substrate to window spacing is 7.5 cm. The gas mixture is Ar/N_2=95/5 at 15 mTorr with a power deposition of 400 W. Although, this is not an etching gas mixture, it does capture many of the features of typical molecular gas mixtures used for etching with the exception of negative ions. The coil has two azimuthal turns, coupled by a radial segment, and is fed by 2 axial current segments. The physical inductance of the coil is $\approx 1.8\ \mu$H. Asymmetries have purposely been built into the reactor for demonstration purposes. The first asymmetry is a wafer handler port leading to a load lock. The load lock bay is an opening in the outer wall of the reactor having an extended sized to

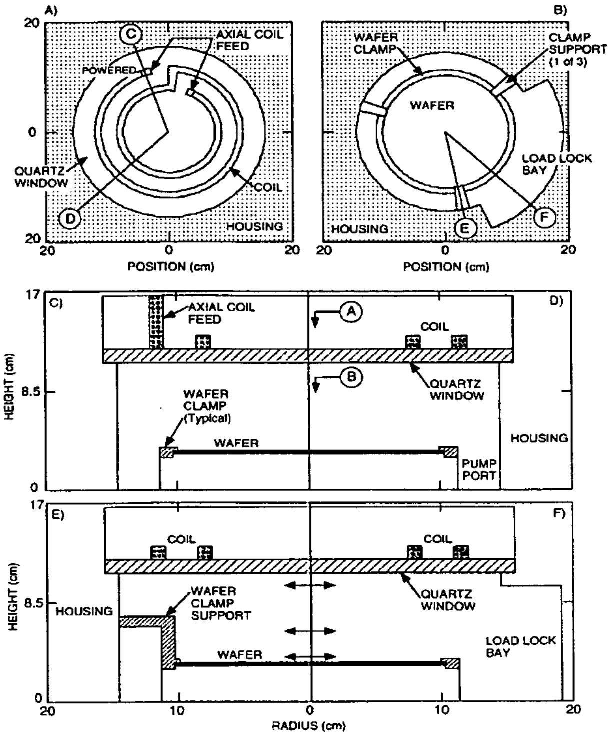

FIG. 1. Schematic of the ICP geometry used in this study. (a) Downward looking view of the top of the coil. The coil has two turns with a radial coupling segment, and is fed by two axial segments. The coil feed along section C is powered; the other feed is terminated. [See (d) for the axial location of this view.] (b) Downward looking view of the chamber from the just below the quartz window. The outline of the wafer clamp support structure, substrate, wafer, and load lock bay are shown. [See (d) for the axial location of this view.] (c)-(f) Radial sections of the reactor at 4 azimuthal locations. [The azimuthal location of the radial sections are shown by the section markers in (a)].

accept the wafer. The second asymmetry consists of 3 dielectric support structures for the wafer clamp. The computational mesh is approximately 45×60 mesh points in the (r,z) plane and 48 θ planes in the azimuthal direction. The species included in the simulation are electrons, Ar, Ar(4s), Ar^+, N_2, and N_2^+. The electron impact and heavy particle reactions for these chemistries are discussed in Refs. 7 and 15. In addition to those processes, we include charge exchange between Ar^+ and N_2, and quenching of Ar(4s) by collisions with N_2.

One of the most important characteristics which determine the azimuthal symmetry of the plasma are the circuit parameters of the coil. Two critical components in this regard are the amount of capacitive coupling from the coil to the plasma (or other metal structures) and the discrete termination impedance to the coil, in these cases a capacitance. Finite capacitive coupling from the coil reduces the conduction current along the path of the coil, thereby reducing the magnitude of the local inductive electric field. This capacitive coupling is controlled, in part by the cross sectional shape of the coil and its proximity to the plasma. The termination capacitance determines the location of the voltage zero crossings (and current maxima) in the standing wave

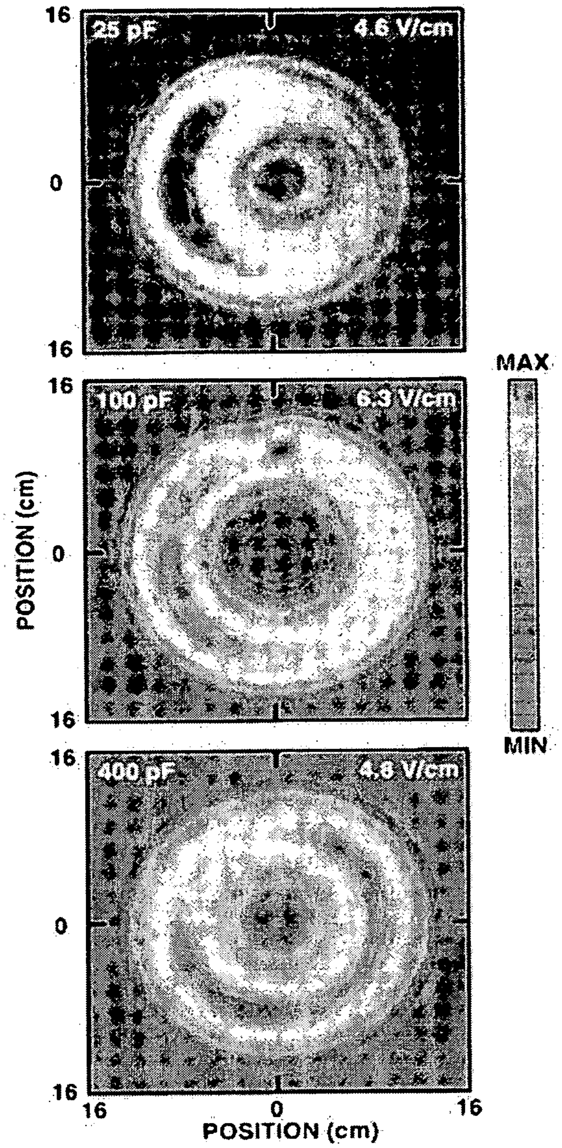

FIG. 2. Magnitude of the inductively coupled electric field in the plasma for a (r,θ) slice $\approx$0.5 cm below the quartz window. Results are shown for termination impedances of the coil of 25, 100, and 400 pF. The maximum value of the electric field is shown at the top. The azimuthal symmetry of the electric field improves with increasing termination capacitance while the peak in the electric field rotates in angle.

along the transmission line.[12] For example, the magnitude of the inductively coupled electric field in a plane $\approx$0.5 cm below the quartz window is shown in Fig. 2 for termination impedances of 25 pF, 100 pF, and 400 pF. The capacitive coupling of the coil is $\approx$1 pF/cm of length while the skin depth in the plasma is $\approx$1.5–2 cm. For these conditions, the symmetry of the electric field improves and the location of the maximum in the electric field rotates as the termination capacitance increases. Maximum electric fields range from 4.5 to 6.5 V/cm. Although, the electric fields are dominated by the azimuthal component, the radial, and axial components do make significant contributions. For example, the "hot spot" in the electric field at the top of the figure for the case using a 100 pF termination impedance corresponds to the radial coil segment joining the two annuli. The local minimum in electric field close to the "hot spot" corresponds to the gap in the coil in the outer turn. The scaling shown here, that of improved uniformity with increasing termination capacitance, is not a general result since the electric field parameters depend, for example, on the degree of capacitive coupling and geometry of the coils.

The scaling shown in Fig. 2 correlates well with the transmission line characteristics of the coil and plasma for a system in which the length of the coil is less than 1/4 wavelength. In the absence of the termination capacitance, the reactance of the coil is $\approx$390 Ω. With a small termination capacitance (25 pF), the termination reactance ($\approx$480 Ω) is larger than that of the coil. The current should therefore decrease along the coil, producing a maximum in the electric field near the input, which is observed. For a large termination (400 pF), the termination reactance is smaller ($\approx$30 Ω) than that of the coil. The current should therefore increase along the coil, producing an electric field which peaks nearer the termination, which is also observed.

The total ion density and electron temperature are shown in Fig. 3 for the Ar/N_2 plasma at different axial locations. [The heights of these (r,θ) "slices" are indicated by the double arrows in Figs. 1(e) and 1(f).] The outlines of structural members in the reactor are shown in white. The lowest (r,θ) slice is a few mm of above the wafer and within the confines of the wafer clamp. The highest (r,θ) slice is between the top of the load lock bay and the quartz window. The termination impedance is 80 pF and the capacitive coil coupling is $\approx$1 pF/cm. These circuit values and geometries were purposely chosen to demonstrate asymmetries in plasma conditions and should not be considered as being optimized in any way. These circuit values do, however, represent typical component values which are encountered in construction of the coils.

The electron temperature is 4.2–4.4 eV directly under the quartz window in an annular region corresponding to the annular electric field. There is, however, a peak in the electron temperature on the left side of the reactor under the quartz window where there is a peak in the electric field and power deposition (see Fig. 2). This electric field distribution produces a local maximum in both ion production and plasma potential. The high thermal conductivity of the plasma disperses the maximum in the electron temperature in the azimuthal direction and fills in the central cool region, so that near the substrate the electron temperature is significantly more uniform than near the quartz window. There remains, however, a vestige of the electron temperature "hot spot" as low as the plane of the wafer.

The ion density has a maximum value of $\approx 1.5\times10^{11}$ cm^{-3} approximately 2.5 cm below the quartz window. Near the quartz window [the highest (r,θ) slice in Fig. 3], there is a local azimuthal maximum in the ion density in the lower left quadrant of the reactor, located near the azimuth where there is a peak in the electron temperature. The locally high electron temperature produces higher ionization rates at that

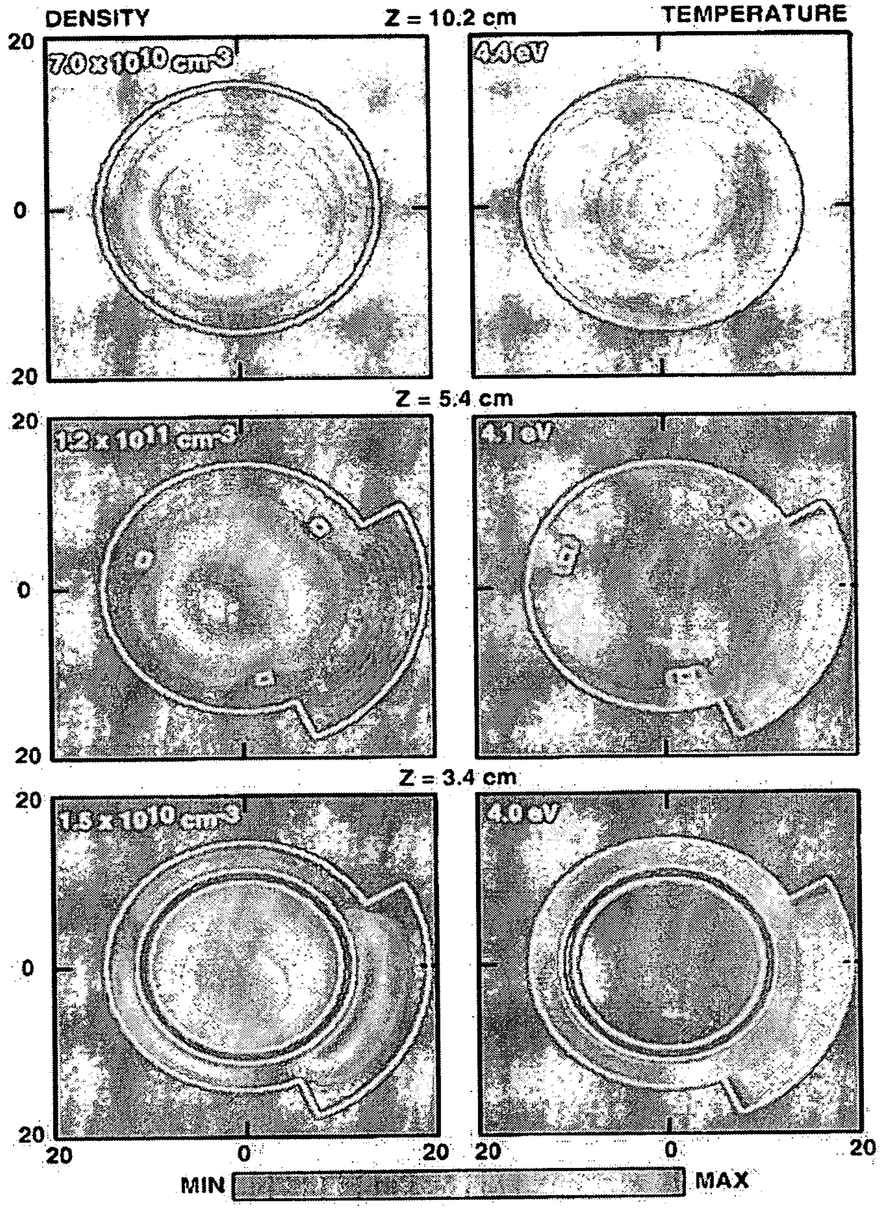

FIG. 3. Total ion density (left) and electron temperature (right) for (r,θ) slices at difference axial locations. The axial locations are shown by the double arrows in Figs. 1(e) and 1(f). The termination impedance 80 pF. The maximum value for the ion density or electron temperature in each frame is indicated in the figure. The local maximum in electric field just below the quartz window produces a maximum in power deposition, electron temperature, and ion source. The wafer clamp support structures and load lock opening perturb the plasma density by altering the local diffusion lengths.

location. The peak in the ionization rate near the quartz window, though dispersed by diffusion, is still evident at the plane of the wafer [the lowest (r,θ) slice in Fig. 3]. The wafer clamp support posts provide recombination surfaces for the plasma, which produce a lower plasma density extending a few cm beyond the posts. This can be seen in the middle (r,θ) slice in Fig. 3. The ion diffusion losses to the wafer clamp support structures contribute to lower ion densities at the plane wafer at their azimuths. The plasma density has a local maximum in the opening to the load lock bay. This local maximum is due to the locally longer diffusion length into the load lock bay which results in lower rates of ion loss to the walls. This also results in there being a lower rate of plasma loss from the volume above the wafer at those azimuthal locations. The end result is a small amount of ''skewing'' of the ion density towards the load lock bay opening.

The fact that the antenna generated azimuthal asymmetries in plasma production can persist to the plane of the wafer places added importance on proper coil design. To isolate these effects, experiments and modeling were per-

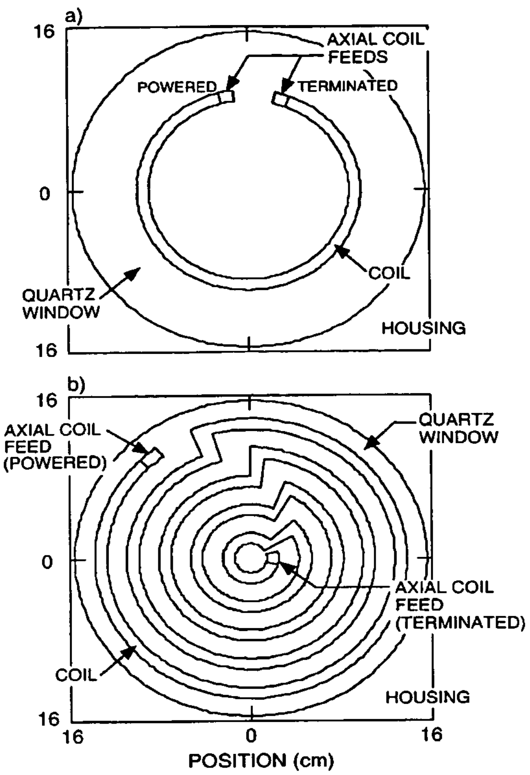

FIG. 4. Coil patterns for comparison of ICP reactors having (a) one-turn and (b) five-turn antennas. The location of the powered and terminated current feeds are shown. The coils are terminated with a 80 pF capacitor to ground.

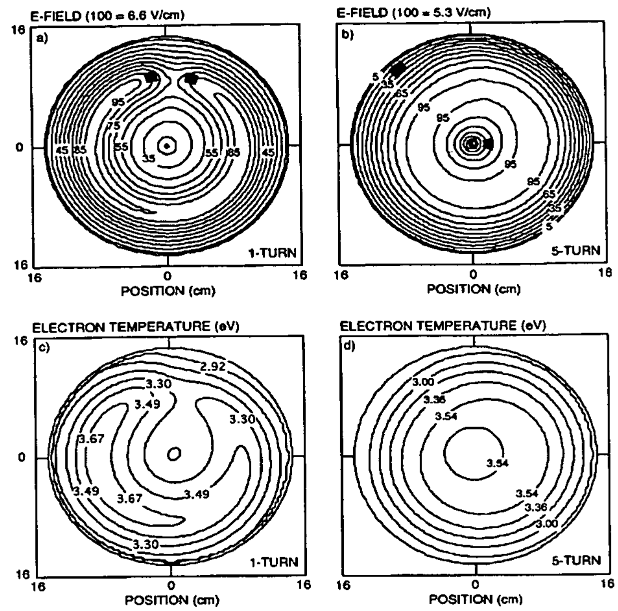

FIG. 5. Predicted parameters for ICP reactors having one-turn and five-turn coils. (a)–(b) Inductively coupled electric fields 0.5 cm below the quartz window and (c)–(d) electron temperature. The plasma conditions are 5 mTorr of Cl_2 and an ICP power deposition of 250 W. The contour labels are the percent of the maximum value indicated in each figure. For reference, the locations of the current feeds are indicated. The reactor having the one-turn coil produces an asymmetric electric field and a commensurate asymmetry in the electron temperature.

formed on an ICP reactor whose internal structures were symmetric in the azimuthal direction. For these cases, we removed the load lock bay and wafer clamp support structures from the computational geometry discussed above. The only asymmetries are with the coil. Two designs which use one- and five-turn coils were experimentally and computationally investigated. The plasmas were sustained in 5 mTorr of Cl_2 with 250 W of power deposition while etching 200 mm diam poly-silicon wafers. Ion densities were obtained by measuring ion saturation current with a Langmuir probe. In modeling these experiments, the species we included are Cl_2, Cl_2^+, Cl, Cl^+, Cl^-, and Cl*. The reaction mechanisms are the same as discussed in Ref. 7. The coil patterns we used in the simulation are shown in Fig. 4. The coils were terminated with 80 nF capacitors. The physical inductance of the one- and five-turn coils in the model were 1.0 μF and 3.6 μF with capacitive coupling of 1pF/cm, commensurate with experimental measurements of the electrical properties of the coils.

The computed inductively coupled electric fields and electron temperature for the one- and five-turn coils at a plane $\approx$0.5 cm under the quartz window are shown in Fig. 5. The electric field for the one-turn coil is asymmetric and has an amplitude 10%–15% higher on the side of the reactor adjacent to the powered current feed. The electric field for the five-turn coil is more uniform in the azimuth, but does have a small azimuthal maximum in the lower right quadrant. The azimuthal nonuniformities in electric field produce corresponding nonuniformities in the electron temperature. The electron temperature for the one-turn coil peaks on the left side of the reactor, while that for the five-turn coil is skewed towards the lower right quadrant.

These asymmetries in electron temperature produce asymmetries in ionization rate and ultimately ion densities which persist to the plane of the wafer. For example, experimental and model derived values for ion density as a function of azimuth are shown in Fig. 6 for the one- and five-turn coil reactors. These values are for ion densities $\approx$1 cm above the edge of the wafer. The azimuthal angle is measured with respect to the axial current feed on the powered side of the coil. For the one-turn coil, there is an azimuthal variation in ion density of approximately $\pm$20% whose maximum maps (in angle) to the maximum in electron temperature at the plane of the quartz window. The ion density with the five-turn coil is significantly more uniform as a function of azimuth.

For these plasma conditions, the poly-silicon etch rate is in the "ion starved" regime. Although, the etching is dominantly by neutral Cl atoms, the uniformity of etching is largely determined by the ion flux uniformity. This is particularly true in Cl_2 plasmas where the Cl atom has a low reactive sticking coefficient on side walls, and therefore has a fairly uniform distribution throughout the reactor even though it may be produced nonuniformly. Experimental

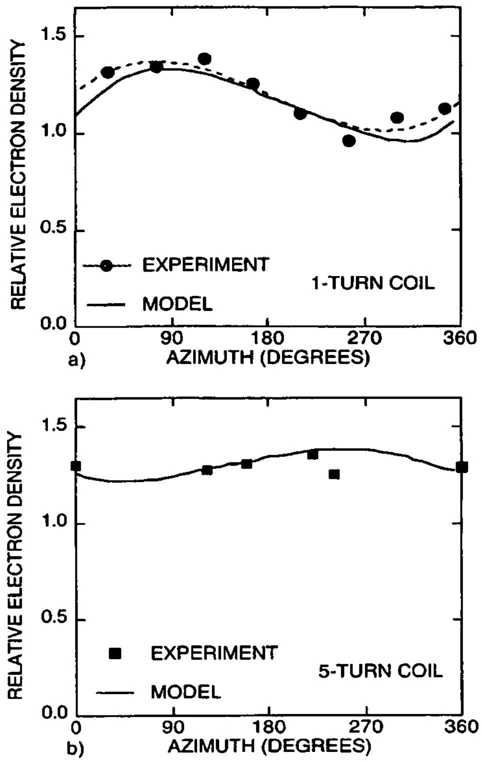

FIG. 6. Experiment and model derived ion densities 1 cm above the edge of the wafer as a function of azimuth location for (a) one-turn and (b) five-turn coils. The reactor with the one-turn coil has a significant azimuthal variation in the ion density. The discharge conditions are 5 mTorr of Cl_2 with 250 W ICP power.

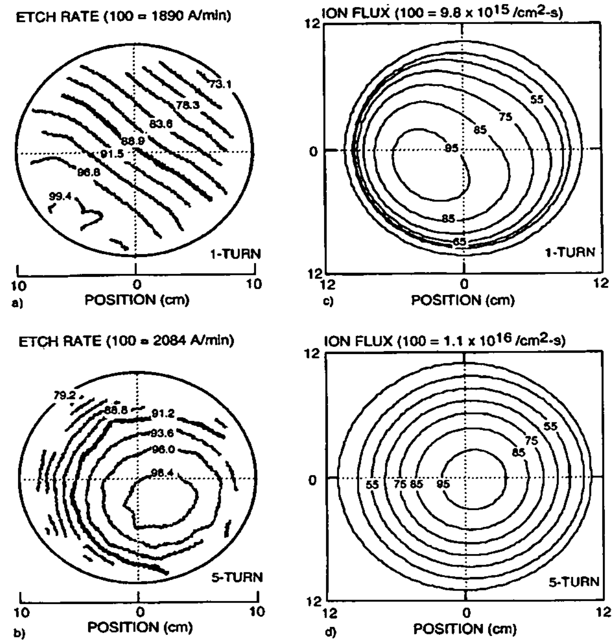

FIG. 7. Etch profiles and ion fluxes to the wafer for reactors having one- and five-turn coils with plasmas sustained in 5 mTorr of Cl_2 with 250 W ICP power. (a) and (b) Experimental etch rates for poly-silicon. (c) and (d) Predicted ion fluxes to the wafer.

measurements of the poly-silicon etch rates and model predictions for the ion flux to the wafer for the one- and five-turn coil geometries are shown in Fig. 7. The ion flux is the sum of the fluxes for Cl_2^+ and Cl^+. The peak etch rates are approximately 1890 Å/min for the one-turn coil and 2084 Å/min for the five-turn coil, a ratio of 1.1. The peak ion fluxes are 9.8×10^{15} and 1.1×10^{16} cm^{-2} s^{-1}, respectively, also a ratio of 1.1. For the one-turn coil, the etch rate shows a side-to-side variation, with the maximum at an azimuth corresponding to the peak in the calculated and measured ion density above the edge of the wafer. The ion flux to the wafer obtained from the model reproduces this trend. For the five-turn coil, the side-to-side variation in etch rate has been significantly reduced and the etch rate is more symmetric as a function of azimuth. There is, however, a shift in the center of symmetry of the etch rate to the right lower quadrant. The predicted ion flux to the wafer also has a shift towards the right lower quadrant. The azimuth at which the etch rate is a maximum maps to the azimuth of the maximum in the ion density. The small differences in the precise azimuth of the maxima in the experimental etch rates and predicted ion fluxes are due to small differences in the value of the termination impedence.

IV. CONCLUDING REMARKS

In conclusion, a three-dimensional model for inductively coupled plasma etching reactors has been presented. The consequences of coil design and asymmetries in the chamber construction on the plasma properties have been discussed. The uniformity of plasma production can be largely controlled by proper selection of circuit elements which determine the capacitive currents and standing wave pattern for the coil. We showed that azimuthal and side-to-side asymmetries in etch rates can be directly correlated to similar asymmetries in the inductively coupled electric field and ion production rates. These asymmetries persist to the plane of the wafer. Proper coil design can eliminate these asymmetries and produce azimuthally symmetric etching rates.

ACKNOWLEDGMENTS

The work performed at the University of Illinois was supported by Sandia National Laboratory/Sematech, the Semiconductor Research Corp., LAM Research Corp., the National Science Foundation (ECS 94-04133, CTS 94-12565), and the University of Wisconsin ERC for Plasma Aided Manufacturing.

[1] J. Hopwood, Plasma Sources Sci. Technol. **3**, 640 (1994).
[2] J. H. Keller, J. C. Forster, and M. S. Barnes, J. Vac. Sci. Technol. A **11**, 2487 (1993).
[3] M. S. Barnes, J. C. Forster, and J. H. Keller, Appl. Phys. Lett. **62**, 2622 (1993).
[4] R. Patrick, R. Schoenborn, and H. Toda, J. Vac. Sci. Technol. A **11**, 1296 (1993).

[5] L. J. Mahoney, A. E. Wendt, E. Barrios, C. J. Richards, and J. L. Shohet, J. Appl. Phys. **76**, 2041 (1994).
[6] J. Holland, V. Singh, F. Lin, and M. Barnes, Program of the 42nd Annual Symposium of the American Vacuum Society, Denver, CO, 1995 paper PS-TuP8 (unpublished), and J. Holland (private communication).
[7] P. L. G. Ventzek, M. J. Grapperhaus, and M. J. Kushner, J. Vac. Sci. Technol. B **12**, 3118 (1994).
[8] R. A. Stewart, P. Vitello, D. B. Graves, E. F. Jaeger, and L. A. Berry, Plasma Sources Sci. Technol. **4**, 36 (1995).
[9] G. Dipeso, V. Vahedi, D. W. Hewett, and T. D. Rognlien, J. Vac. Sci. Technol. A **12**, 1387 (1994).
[10] D. L. Lymberopoulos and D. Economou, Trans. Plasma Sci. **23**, 573 (1995).
[11] W. Collison and M. J. Kushner, Appl. Phys. Lett. **68**, 903 (1996).
[12] J. F. Jaeger, L. A. Berry, J. S. Tolliver, and D. B. Batchelor, J. Phys. Fluids **2**, 2597 (1995).
[13] R. B. Piejak, V. A. Godyak, and B. M. Alexandrovich, Plasma Sources Sci. Tech. **1**, 179 (1992).
[14] See, for example, W. L. Morgan and B. M. Penetrante, Comp. Phys. Comm. **58**, 127 (1990).
[15] T. J. Sommerer and M. J. Kushner, J. Appl. Phys. **71**, 1654 (1992).

THE AMERICAN HERITAGE DICTIONARY OF THE ENGLISH LANGUAGE

THIRD EDITION

HOUGHTON MIFFLIN COMPANY
Boston · New York · London


fret[3]


Sigmund Freud


Frey


Freya
With attendants

ă pat	oi boy
ā pay	ou out
âr care	ŏŏ took
ä father	ōō boot
ĕ pet	ŭ cut
ē be	ûr urge
ĭ pit	th thin
ī pie	*th* this
îr pier	hw which
ŏ pot	zh vision
ō toe	ə about, item
ô paw	♦ regionalism

Stress marks: ′ (primary); ′ (secondary), as in dictionary (dĭk′shə-nĕr′ē)

Tuamotu archipelago. It was organized as a territory in 1903. Papeete, on the island of Tahiti, is the capital. Population, 166,753.

French provincial *n.* A style of architecture or furniture characteristic of the provinces in 17th- and 18th-century France.

French seam *n.* A seam stitched first on the right side and then turned in and stitched on the wrong side so that the raw edges are enclosed in the seam.

French toast *n.* Sliced bread soaked in a batter of milk and egg and lightly fried.

French West Af·ri·ca (ăf′rĭ-kə). A former federation of western Africa (1895–1959) comprising the present-day countries of Benin, Guinea, Ivory Coast, Mali, Mauritania, Niger, Senegal, and Burkina Faso.

French West In·dies (ĭn′dēz). The French overseas departments of Guadeloupe and Martinique in the Lesser Antilles.

French window *n.* **1.** A pair or one of a pair of windows extending to the floor and opening in the middle. **2.** A casement window.

French·wom·an (frĕnch′wŏŏm′ən) *n.* A woman who is a native or inhabitant of France.

Fre·neau (frĭ-nō′), **Philip Morin.** Known as "the poet of the American Revolution." 1752–1832. American poet noted for his satirical attacks on the British.

fre·net·ic or **phre·net·ic** (frə-nĕt′ĭk) also **fre·net·i·cal** or **phre·net·i·cal** (-ĭ-kəl) *adj.* Wildly excited or active; frantic; frenzied. [Middle English *frenetik,* from Old French *frenetique,* from Latin *phrenēticus,* from Greek *phrenitikos,* from *phrenitis,* brain disease, from *phrēn,* mind. See **gʷhren-** in Appendix.] —**fre·net′i·cal·ly** *adv.* —**fre·net′i·cism** (-ĭ-sĭz′əm) *n.*

fren·u·lum (frĕn′yə-ləm) *n., pl.* **-la** (-lə). **1.** *Anatomy.* A small frenum. **2.** *Entomology.* A bristly structure on the hind wings of certain moths and butterflies that holds the forewings and hind wings together during flight. [New Latin, diminutive of Latin *frēnum,* bridle, from *frendere,* to grind. See **ghrendh-** in Appendix.]

fre·num (frē′nəm) *n., pl.* **-nums** or **-na** (-nə). *Anatomy.* A membranous fold of skin or mucous membrane that supports or restricts the movement of a part or organ, such as the small band of tissue that connects the underside of the tongue to the floor of the mouth. [Latin *frēnum,* bridle, from *frendere,* to grind. See **ghrendh-** in Appendix.]

fren·zied (frĕn′zēd) *adj.* Affected with or marked by frenzy; frantic: *a frenzied rush for the exits.* —**fren′zied·ly** *adv.*

fren·zy (frĕn′zē) *n., pl.* **-zies. 1.** A state of violent mental agitation or wild excitement. **2.** Temporary madness or delirium. **3.** A mania; a craze. —**frenzy** *tr.v.* **-zied, -zy·ing, -zies.** To drive into a frenzy. [Middle English *frenesie,* from Old French, from Medieval Latin *phrenēsia,* from Latin *phrenēsis,* back-formation from *phrenēticus,* delirious. See FRENETIC.]

Fre·on (frē′ŏn′). A trademark used for a variety of nonflammable gaseous or liquid fluorinated hydrocarbons employed primarily as working fluids in refrigeration and air conditioning and as aerosol propellants.

freq. *abbr.* **1.** Frequency. **2.** *Grammar.* Frequentative. **3.** Frequently.

fre·quence (frē′kwəns) *n.* Frequency. [Middle English, multitude, from Old French, from Latin *frequentia.* See FREQUENCY.]

fre·quen·cy (frē′kwən-sē) *n., pl.* **-cies.** *Abbr.* **freq. 1.** The property or condition of occurring at frequent intervals. **2.** *Mathematics & Physics.* The number of times a specified phenomenon occurs within a specified interval, as: **a.** The number of repetitions of a complete sequence of values of a periodic function per unit variation of an independent variable. **b.** The number of complete cycles of a periodic process occurring per unit time. **c.** The number of repetitions per unit time of a complete waveform, as of an electric current. **3.** *Statistics.* **a.** The number of measurements in an interval of a frequency distribution. **b.** The ratio of the number of times an event occurs in a series of trials of a chance experiment to the number of trials of the experiment performed. [Latin *frequentia,* multitude, from *frequēns, frequent-,* crowded, numerous, frequent.]

frequency distribution *n.* *Statistics.* A set of intervals, usually adjacent and of equal width, into which the range of a statistical distribution is divided, each associated with a frequency indicating the number of measurements in that interval.

frequency modulation *n.* *Abbr.* **FM, fm** The encoding of a carrier wave by variation of its frequency in accordance with an input signal.

fre·quent (frē′kwənt) *adj.* Occurring or appearing quite often or at close intervals: *frequent errors of judgment.* —**frequent** (*also* frē-kwĕnt′) *tr.v.* **-quent·ed, -quent·ing, -quents.** To pay frequent visits to; be in or at often: *frequent a restaurant.* [Middle English, ample, profuse, from Old French, from Latin *frequēns, frequent-,* crowded, numerous, frequent.] —**fre′quen·ta′tion** *n.* —**fre·quent′er** (-kwĕn′tər) *n.* —**fre′quent·ness** *n.*

fre·quen·ta·tive (frē-kwĕn′tə-tĭv) *Grammar. adj.* *Abbr.* **freq.** Expressing repeated action. —**frequentative** *n.* *Abbr.* **freq.** A frequentative verb or verb form.

frequent flier *n.* One who travels often by air, especially on one airline.

fre·quent·ly (frē′kwənt-lē) *adv.* *Abbr.* **freq.** At frequent intervals; often.

fres·co (frĕs′kō) *n., pl.* **-coes** or **-cos. 1.** The art of painting on fresh, moist plaster with pigments dissolved in painting executed in this way. —**fresco** *tr.v.* **-co -coes.** To paint in fresco. [Italian, fresh (plaster), origin.] —**fres′co·er, fres′co·ist** *n.*

fresh (frĕsh) *adj.* **fresh·er, fresh·est. 1.** New t rience; not encountered before. **2.** Novel; different: *on the problem.* See Synonyms at **new. 3.** Recentl duced, or harvested; not stale or spoiled: *fresh bread.* served, as by canning, smoking, or freezing: *fresh v* Not saline or salty: *fresh water.* **6.** Not yet used or *a fresh sheet of paper.* **7.** Free from impurity or pol *fresh air.* **8.** Additional; new: *fresh evidence.* **9.** clear; not dull or faded: *a fresh memory.* **10.** Having unspoiled appearance of youth: *a fresh complexion.* inexperienced: *fresh recruits.* **12.** Having just arri *fashions fresh from Paris.* **13.** Revived or reinv freshed: *I was fresh as a daisy after the nap.* **14.** F brisk: *a fresh wind.* **15.** *Informal.* Bold and saucy; in Having recently calved and therefore with milk. Us —**fresh** *adv.* Recently; newly: *fresh out of milk; m fresh daily.* —**fresh** *n.* **1.** The early part: *the fresh o* A freshet. [Middle English, from Old English *fer* salty, and from Old French *freis* (feminine *fresche*), n Germanic origin.] —**fresh′ly** *adv.* —**fresh′ness** *n*

fresh breeze *n.* *Meteorology.* A wind with a spe to 24 miles (30 to 38 kilometers) per hour, according fort scale.

fresh·en (frĕsh′ən) *v.* **-ened, -en·ing, -ens.** – become fresh, as in vigor or appearance: *freshened day's work.* **2.** To become brisk; increase in strength wind. **3.** To lose saltiness. **4.** To calve and there produce milk. Used of a cow. —*tr.* **1.** To make fres to or strengthen (a drink). —**fresh′en·er** *n.*

fresh·et (frĕsh′ĭt) *n.* **1.** A sudden overflow of a s ing from a heavy rain or a thaw. **2.** A stream of fre empties into a body of salt water.

fresh gale *n.* *Meteorology.* A wind with a speed 46 miles (62 to 74 kilometers) per hour, according to scale.

fresh·man (frĕsh′mən) *n.* **1.** A student in the fi of a high school, college, or university. **2.** A begin See Usage Note at **man.** —*attributive.* Often used t other noun: *in my freshman year; a freshman senat*

fresh·wa·ter (frĕsh′wô′tər, -wŏt′ər) *adj.* **1.** Of living in, or consisting of water that is not salty: *fre freshwater lakes.* **2.** Situated away from the sea; inla *tical.* Accustomed to sailing on inland waters only: *sailor.*

Fres·nel (frā-nĕl′), **Augustin Jean.** 1788–1827. F icist who supported the wave theory of light, investi ized light, and developed a compound lens for use in

Fres·nel lens (frə-nĕl′) *n.* A thin optical lens concentric rings of segmental lenses and having a length, used primarily in spotlights, beacons, and the motor vehicles. [After Augustin Jean FRESNEL.]

Fres·no (frĕz′nō). A city of central California sou of Sacramento in the San Joaquin Valley. Populatio

fret[1] (frĕt) *v.* **fret·ted, fret·ting, frets.** —*tr.* **1.** T uneasy; vex: *"fret thy soul with crosses and with car* Spenser). **2. a.** To gnaw or wear away; erode. **b.** hole or worn spot in; corrode. See Synonyms at **chafe.** (a passage or channel) by erosion. **4.** To disturb t (water or a stream); agitate. —*intr.* **1.** To be vexed worry. See Synonyms at **brood. 2.** To be worn or become corroded. **3.** To move agitatedly. **4.** To g teeth in the manner of a rodent. —**fret** *n.* **1.** The stance of fretting. **2.** A hole or worn spot made by erosion. **3.** Irritation of mind; agitation. [Middle E from Old English *fretan,* to devour. See **ed-** in App

fret[2] (frĕt) *Music. n.* One of several ridges set acro board of a stringed instrument, such as a guitar. —**fr ted, fret·ting, frets. 1.** To provide with frets. **2.** strings of an instrument) against the frets. [Origin

fret[3] (frĕt) *n.* **1.** An ornamental design consisting and symmetrical figures, often in relief, contained w or border. **2.** A headdress, worn by women of the consisting of interlaced wire. —**fret** *tr.v.* **fret·te frets.** To provide with such a design or headdress. [lish, interlaced work, from Old French *frete.*]

fret·ful (frĕt′fəl) *adj.* **1.** Inclined to be vexed or tr vish. **2.** Marked by worry and distress; troublesome *fretful stages of human development, adolescence is famous"* (David Gelman). —**fret′ful·ly** *adv.* —**fret**

fret saw *n.* A long, narrow-bladed saw with fine t making curved cuts in thin wood or metal.

fret·work (frĕt′wûrk′) *n.* **1.** Ornamental work three-dimensional frets; geometric openwork. **2.** Su tal work represented two dimensionally by chiarosc

Freud (froid), **Anna.** 1895–1982. Austrian-born Br analyst noted for her theories about child therapy.

Freud, Sigmund. 1856–1939. Austrian physician of psychoanalysis who theorized that the symptoms patients represent forgotten and unresolved infantil ual conflicts.

French, from Latin *paupertās,* from *pauper,* poor. See **pau-** in Appendix.]

poverty grass *n.* Any of several North American grasses that grow in poor or sandy soil.

poverty level *n.* A minimum income level below which a person is officially considered to lack adequate subsistence and to be living in poverty. Also called *poverty line.*

pov·er·ty-strick·en (pŏv′ər-tē-strĭk′ən) *adj.* Suffering from poverty; miserably poor. See Synonyms at **poor.**

POW (pē′ō-dŭb′əl-yo͞o, -yo͞o) *n., pl.* **POW's** also **POWs.** A prisoner of war.

Pow·ay (pou′ā). A community of southern California north of San Diego. It is near a large naval air base. Population, 33,300.

pow·der (pou′dər) *n.* **1.** A substance consisting of ground, pulverized, or otherwise finely dispersed solid particles. **2.** Any of various preparations in the form of powder, as certain cosmetics and medicines. **3.** An explosive mixture, such as gunpowder. **4.** Light, dry snow. —**powder** *v.* **-dered, -der·ing, -ders.** —*tr.* **1.** To reduce to powder; pulverize. **2.** To dust or cover with or as if with powder. **3.** *Slang.* To defeat handily or decisively. —*intr.* **1.** To become pulverized; turn into powder. **2.** To use powder as a cosmetic. —***idioms.*** **keep (one's) powder dry.** To be ready for a challenge with little warning. **take a powder.** To make a quick departure; run away. [Middle English *poudre,* from Old French, from Latin *pulvis, pulver-.*] —**pow′der·er** *n.*

powder horn
1767 American

powder blue *n. Color.* A moderate to pale blue or purplish blue. [From the color of powdered smalt.]

powder horn *n.* An animal's horn capped at the open end, used to carry gunpowder.

powder keg *n.* **1.** A small cask for holding gunpowder or other explosives. **2.** A potentially explosive situation or thing.

Pow·der·ly (pou′dər-lē), **Terence Vincent.** 1849–1924. American labor leader who directed the Knights of Labor, a secret organization that disavowed strikes, during its period of greatest influence (1879–1893).

powder metallurgy *n.* The technology of powdered metals, especially the production and utilization of metallic powders for fabricating massive materials and shaped objects.

powder monkey *n. Slang.* One who carries or sets explosives.

powder puff *n.* A soft pad for applying powder to the skin.

pow·der-puff (pou′dər-pŭf′) *adj.* Of, relating to, or being a usually competitive activity in which only women take part: *powder-puff baseball.*

Pow·der River (pou′dər). A river rising in several branches in the Bighorn Mountains of central Wyoming and flowing about 782 km (486 mi) generally northeast into southern Montana.

powder room *n.* **1.** A lavatory for women. **2.** A lavatory for guests in a private home.

pow·der·y (pou′də-rē) *adj.* **1.** Composed of or similar to powder. **2.** Dusted or covered with or as if with powder. **3.** Easily made into powder; friable.

powdery mildew *n.* **1.** Any of various fungi, especially of the family Erysiphaceae, that produce powdery conidia on the host surface. **2.** A plant disease caused by any of these fungi.

Pow·ell (pou′əl), **Adam Clayton, Jr.** 1908–1972. American politician. A U.S. representative from New York (1945–1967 and 1969–1971), he was an outspoken advocate of civil rights.

Powell, Anthony. Born 1905. British writer best known for *A Dance to the Music of Time* (1951–1975), a cycle of 12 satirical novels.

Powell, Cecil Frank. 1903–1969. British physicist. He won a 1950 Nobel Prize for discovering methods of photographing atomic nuclei and for his study of mesons.

Powell, John Wesley. 1834–1902. American geologist and ethnologist who directed the U.S. Geological Survey (1881–1894) and classified many Native American languages.

Powell, Lewis Franklin, Jr. Born 1907. American jurist who served as an associate justice of the U.S. Supreme Court (1971–1987).

pow·er (pou′ər) *n. Abbr.* **pwr. 1.** The ability or capacity to perform or act effectively. **2.** Often **powers.** A specific capacity, faculty, or aptitude: *her powers of concentration.* **3.** Strength or force exerted or capable of being exerted; might. See Synonyms at **strength. 4.** The ability or official capacity to exercise control; authority. **5.** A person, group, or nation having great influence or control over others: *the western powers.* **6.** The might of a nation, political organization, or similar group. **7.** Forcefulness; effectiveness: *a novel of unusual power.* **8.** *Chiefly Upper Southern U.S.* A large number or amount. See Regional Note at **powerful. 9. a.** The energy or motive force by which a physical system or machine is operated: *turbines turned by steam power; a sailing ship driven by wind power.* **b.** The capacity of a system or machine to operate: *a vehicle that runs under its own power.* **c.** Electrical or mechanical energy, especially as used to assist or replace human energy. **d.** Electricity supplied to a home, building, or community: *a storm that cut off power to the whole region.* **10.** *Physics.* The rate at which work is done, expressed as the amount of work per unit time and commonly measured in units such as the watt and horsepower. **11.** *Electricity.* **a.** The product of applied potential difference and current in a direct-current circuit. **b.** The product of the effective values of the voltage and current with the cosine of the phase angle between current and voltage in an alternating-current circuit. **12.** *Mathematics.* **a.** See **exponent** (sense 3). **b.** The number of elements in a finite set. **13.** *Statistics.* The probability of rejecting the null hypothesis where it is false. **14.** A measure of the magnification of an optical instrument, such as a microscope or telescope. **15. powers.** *Theology.* The sixth of the nine orders of angels. **16.** *Archaic.* An armed force. —**power** *adj.* **1.** Of or relating to political, social, or economic control: *a power struggle; a power base.* **2.** Operated with mechanical or electrical energy in place of bodily exertion: *a power tool; power car windows.* **3.** Of or relating to the generation or transmission of electricity: *power companies; power lines.* **4.** *Informal.* Of or relating to influential business or professional practices: *a pinstriped suit with a power tie; met with high-level executives at a power breakfast.* —**power** *tr.v.* **-ered, -er·ing, -ers.** To supply with power, especially mechanical power. —***idiom.*** **powers that be.** Those who hold effective power in a system or situation: *a plan vetoed by the powers that be.* [Middle English, from Old French *poeir,* to be able, power, from Vulgar Latin **potēre,* to be able, from *potis,* able, powerful. See **poti-** in Appendix.]

pow·er·boat (pou′ər-bōt′) *n.* See **motorboat.**

power brake *n.* A motor vehicle brake assisted by a power mechanism operated by the engine that amplifies pressure applied to the brake pedal.

power broker or **pow·er·brok·er** (pou′ər-brō′kər) *n.* A person who exerts strong political or economic influence, especially by virtue of the individuals and votes he or she controls: "A *power broker is someone who can assemble a number of favors due from a coterie of powerful people and then use that agglomeration of . . . favors to work a deal*" (William H. Hallahan).

power dive *n.* A downward plunge of an aircraft accelerated by both gravity and engine power. —**pow′er-dive′** (pou′ər-dīv′) *v.*

power drill *n.* **1.** A portable electric drill. **2.** A large drilling machine having a vertical, motorized drill set in a table stand.

♦**pow·er·ful** (pou′ər-fəl) *adj.* **1.** Having or capable of exerting power. **2.** Effective or potent: *a powerful drug.* **3.** *Computer Science.* Fast, versatile, or able to handle large tasks. Used of hardware or software. **4.** *Chiefly Upper Southern U.S.* Great: *The storm did a powerful lot of harm.* —**powerful** *adv. Chiefly Upper Southern U.S.* Very: *It was powerful humid.* —**pow′er·ful·ly** *adv.* —**pow′er·ful·ness** *n.*

♦***REGIONAL NOTE:*** In the upper southern United States the words *powerful* and *mighty* are intensives used frequently like the adverb *very*: *Your boy's grown powerful big. The new baby is mighty purty. Powerful* is used as an adjective in some expressions: *The storm did a powerful lot of harm.* In the same dialect region the noun *power* has, in addition to its standard meanings, the sense of "a large number or amount." This sense appears in the *Oxford English Dictionary* as common in dialectal British English of the 18th and 19th centuries: "*It has done a power of work*" (Charles Dickens). All these derivative senses of *power* and *might* take advantage of the notion of strength inherent in these nouns, making them natural intensives. Colloquial English is always on the lookout for ways to make language more vivid with new intensives. We think of the upper southern part of the United States as linguistically conservative, but in fact it has preserved uses of *power, powerful,* and *mighty* that were innovative in their time.

pow·er·house (pou′ər-hous′) *n.* **1.** See **power plant** (sense 2). **2.** One that possesses great force or energy: *She is an editorial powerhouse.*

pow·er·less (pou′ər-lĭs) *adj.* **1.** Lacking strength or power; helpless and totally ineffectual. **2.** Lacking legal or other authority. —**pow′er·less·ly** *adv.* —**pow′er·less·ness** *n.*

pow·er·lift·ing (pou′ər-lĭf′tĭng) *n. Sports.* A weightlifting competition in which participants compete in the squat, dead lift, and bench press.

power mower *n.* A lawn mower that is powered by a gasoline or electric motor.

power of appointment *n., pl.* **powers of appointment.** *Law.* Authority granted to one person by another to transfer property upon the death of the latter.

power of attorney *n., pl.* **powers of attorney.** *Abbr.* **P/A** *Law.* A legal instrument authorizing one to act as another's attorney or agent.

power pack *n.* A usually compact, portable device that converts supply current to direct or alternating current as required by specific equipment.

power plant *n.* **1.** All the equipment, including structural members, that constitutes a unit power source: *the power plant of a truck.* **2.** A complex of structures, machinery, and associated equipment for generating electric energy from another source of energy, such as nuclear reactions or a hydroelectric dam. In this sense, also called *powerhouse, power station.*

power play *n.* **1.** *Sports.* **a.** An offensive maneuver in a game, especially in football, in which a massive concentration of players is applied in a certain area. **b.** A situation in ice hockey in which one team has a temporary numerical advantage because the other team has one or more players in the penalty box. **2.** A strategic maneuver, as in politics, diplomacy, or business, based on the use or threatened use of power as a means of coercion.

Houghton Mifflin Company gratefully acknowledges Mead Data Central, Inc., providers of the LEXIS®/NEXIS® services, for its assistance in the preparation of this edition of *The American Heritage Dictionary*.

Library of Congress Cataloging-in-Publication Data

The American heritage dictionary of the English language.
—3rd ed.
p. cm.
ISBN 0-395-44895-6
1. English language—Dictionaries.
PE1628.A623 1992 92-851
423—dc20 CIP

Manufactured in the United States of America

TA